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TUTORIAL PAPERS

Dynamics of fine particles in magnetized plasmas*

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Here are presented experiments on fine particles levitating in low-pressure weakly ionized plasmas under a vertical magnetic field. The magnetic field is useful to provide a vertically long cylindrical column of fine-particle clouds, yielding even string-shaped vertically aligned fine particles, under the double-plasma configuration. Measurements show that fine-particle clouds rotate in the azimuthal direction on the horizontal plane even in such a weak magnetic field that positive ions are slightly magnetized. With an increase of the magnetic field, the rotation speed increases, being followed by subsequent saturation. The rotation speed and direction can be controlled by varying radial plasma potential and/or density profiles. The rotation is induced under the condition that the interparticle distance is small enough for the strong Coulomb coupling among fine particles. A mechanism of the rotation could be explained by effects of ion motions on fine particles, which are modified in the presence of the vertical magnetic field. © 2001 American Institute of Physics. [DOI: 10.1063/1.1342229]

I. INTRODUCTION

Plasmas including fine particles are of current interest in plasma physics and engineering. We have carried out a series of experiments on the dynamics of fine particles in plasmas.^{1–3} One of our interests in fine-particle plasmas has been concerned with fine particles in magnetized plasmas. The magnetic field is useful for shape control of fine-particle clouds. We have also demonstrated a generation of azimuthal rotation of fine-particle clouds in the presence of a weak vertical magnetic field. The results cannot be explained by the $\mathbf{E} \times \mathbf{B}$ motion of electrons, being contrary to the experiment of Fujiyama *et al.*⁴ They observed a clear “back and forth” motion of fine-particle clouds in the $\mathbf{E} \times \mathbf{B}$ direction when an alternative weak magnetic field was applied in the direction perpendicular to a dc electric field. Their experimental configuration is different from the configuration used in our experiments. Following our first observation of the rotation of fine-particle clouds, Konopka *et al.* confirmed this rotation in a rf plasma under a nonuniform magnetic field provided by permanent magnets.⁵

Here are presented more details of our experiments on fine particles in magnetized plasmas. The magnetic field, which is externally applied in the vertical direction, is varied in (1) weak (≤ 0.4 kG), (2) strong (0.4–4 kG), and (3) ultra-strong (4–40 kG) ranges. Roughly speaking, in the range of the weak magnetic field, electrons are magnetized while ions are weakly magnetized. In the range of the strong magnetic field, electrons and ions are magnetized while fine particles are not magnetized. In the range of the ultra-strong magnetic field, fine particles are magnetized in addition to electrons

and ions. Even if the magnetic field is weak, the shapes of fine-particle clouds can be modified by the magnetic field. Measurements show that fine-particle clouds rotate in the azimuthal direction on the horizontal plane in all ranges of the magnetic field, being independent of the shape of the fine-particle clouds. With an increase of the magnetic field, the rotation speed increases, being followed by subsequent saturation. Now we can control the rotation speed and direction by varying a slope of plasma potential and/or density in the radial direction. The results observed are explained by the effects of modified ion motions on fine particles in the presence of vertical magnetic field.

Experimental methods and results obtained are presented in Sec. II. Section III contains discussions and conclusions.

II. EXPERIMENTS

In order to investigate effects of the vertical magnetic field on fine-particle clouds levitating in plasmas, two different kinds of experiments have been carried out in low-pressure weakly ionized plasmas. One of the experiments is concerned with a completely dc configuration, where fine particles are levitated in a diffused plasma. This experiment is concerned with general features of fine-particle clouds in plasmas under the vertical magnetic field. The other experiment is rather specified for detailed measurements of the rotation of fine-particle clouds, which is induced by the vertical magnetic field, where fine-particle clouds are levitated in quite simple configurations of dc and rf discharge plasmas. In both of them, the gas used for plasma production is Ar in the pressure range from a few tens to a few hundreds of mTorr and the plasma density is around $1 \times 10^8 \text{ cm}^{-3}$, and the electron temperature is a few eV. Fine particles used are spherical with $10 \text{ }\mu\text{m}$ in diameter. We have also used fine

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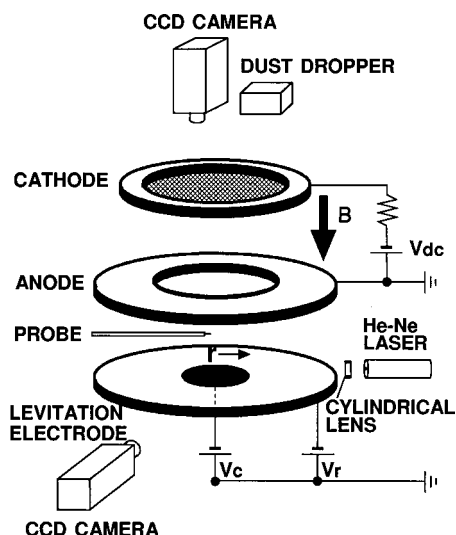


FIG. 1. Standard setup in our experiments on fine-particle plasmas.

particles with different diameters from 0.1 to a few tens of μm . But, from a qualitative point of view, the phenomena observed do not depend on the particle diameter. The vertical magnetic field is smaller than 0.4 kG in the first experiment. But, in the second experiment, we can increase the vertical magnetic field up to 40 kG. Fine particles are detected from the top and side by charge-coupled device (CCD) cameras detecting laser light scattered by fine particles.

A. Shape control and rotation: Diffused plasma

A standard setup for fine-particle clouds in a diffused plasma is shown in Fig. 1, where a plasma is produced by a dc discharge between a mesh cathode and a ring anode. The anode, the hole of which is often covered by mesh, is grounded together with the vacuum chamber. The plasma produced diffuses through the anode into a lower region. Fine particles are levitated by a levitation electrode (disc) and are confined radially by a confinement electrode (ring) in this region. We have performed various kinds of experiments under this dc configuration which is modified for the purposes of the experiments.¹⁻³ At first, we report the shape control of fine-particle clouds in the presence of the vertical magnetic field. Then we present the rotation of fine-particle clouds, which is ascribed to the vertical magnetic field.

1. Shape control of fine-particle clouds

Here we add an auxiliary dc plasma source below the standard setup in Fig. 1. Now we have a double-plasma configuration, as shown schematically in Fig. 2. The plasma produced below also diffuses upward into the experimental region for fine-particle levitation. It can be found in Fig. 2 that the diameter of the auxiliary plasma (AP) is larger than that of the main plasma (MP). Applying an external potential to the AP with respect to the MP, we have two diffusing plasmas with different potentials in the radial direction, which are well separated radially in the presence of vertical magnetic field.

The radial potential profile can be controlled by changing the potential difference applied between the two plasmas. In the vertical direction, there is no appreciable change of

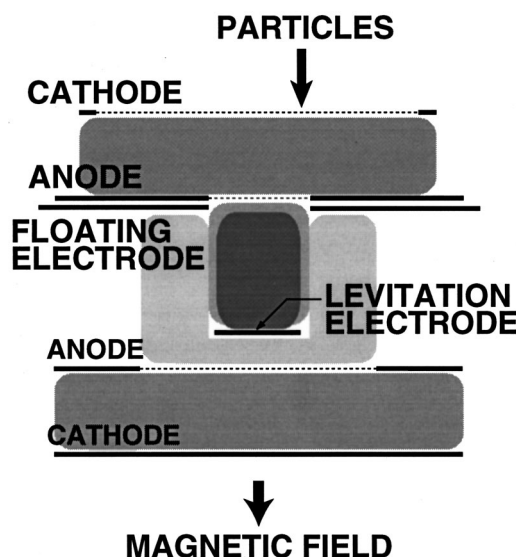


FIG. 2. Schematic of setup for generation of column-shaped fine-particle clouds.

this profile in the presence of vertical magnetic field \mathbf{B} . When we have a hill-shaped potential profile in the radial direction under such a situation, fine particles confined radially spread into an almost all-vertical region up to a position just below the anode of the MP, as demonstrated in Fig. 3. Now the vertical spread is much larger than the radial spread given by the diameter of the levitation electrode, forming the shape of a long cylindrical column in the vertical direction.

Depending on the conditions, this three-dimensional particle cloud becomes unstable, showing a big dynamic mo-

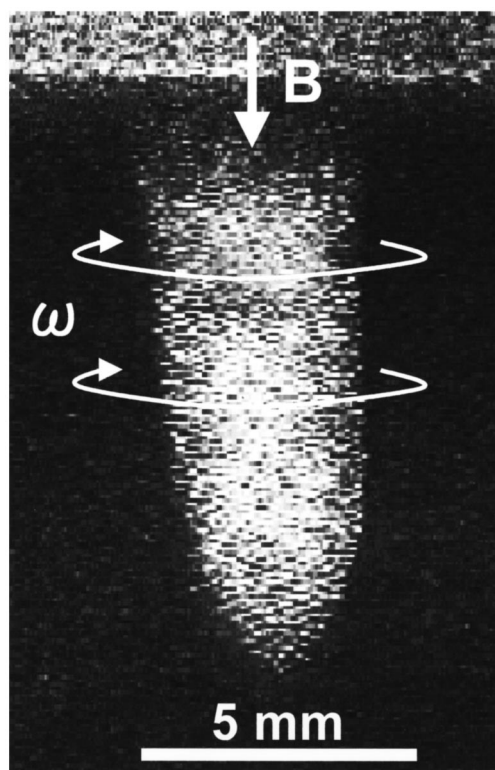


FIG. 3. Typical column-shaped fine particle cloud (side view).

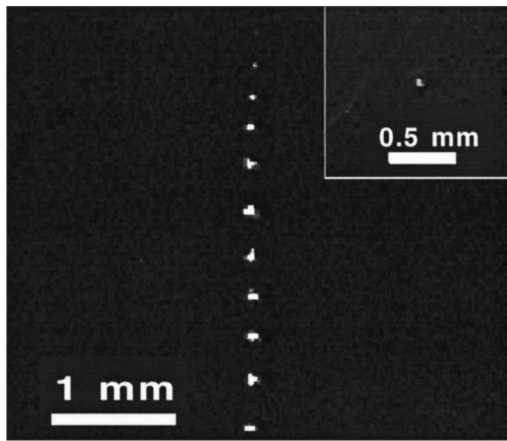


FIG. 4. Vertically aligned fine particles (side view of one string). Inset: top view.

tion. Then, there appear fine-particle acoustic waves propagating toward the levitation electrode and/or vortices associated with “up and down” motions of the particles in fine-particle clouds.

When the width of the radial potential profile is decreased under the double-plasma configuration mentioned above, the column diameter decreases. A further decrease in the profile width, which is provided by decreasing the diameter of the levitation electrode, yields string-shaped vertically aligned fine particles in a row. As an example of these string-shaped fine particles, the observation from the side is demonstrated in the case of one row of fine particles in the vertical direction (see Fig. 4). They line up with almost equal distance between the neighboring particles in the vertical direction. The number of rows is observed to increase gradually, for example, from one to ten or so with an increase in the particle number supplied.

2. Rotation of fine-particle clouds

In this experiment, the weak vertical magnetic field \mathbf{B} up to 0.4 kG is applied to our standard setup in Fig. 1. Although the magnetic field applied is weak, there appears an azimuthal rotation of fine-particle clouds on the horizontal plane. The rotation is in the diamagnetic direction in this case. In Fig. 5, the rotation speeds are plotted as a function of

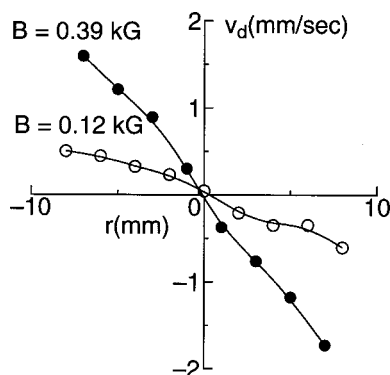


FIG. 5. Rotation speed v_d as a function of radial distance r at vertical magnetic field $\mathbf{B}=0.12$ and 0.39 kG. Gas pressure = 220 mTorr, Discharge current = 0.5 mA.

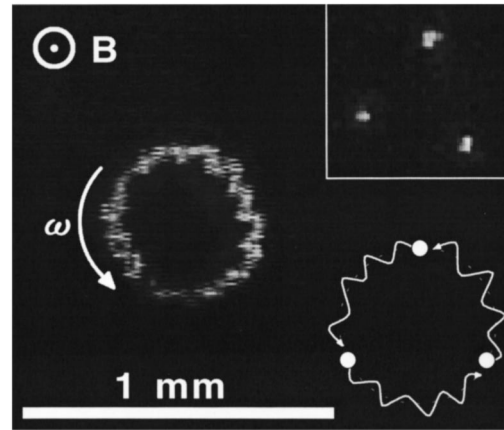


FIG. 6. Rotation of three strings with vertically aligned fine particles (top view). The left figure shows a 15-overlapping (0.45 s) video frame. The right figure (lower) shows orbits following fine-particle motions. Inset : top view at some instant.

the radial distance r at $\mathbf{B}=0.12$ and 0.39 kG. It can be found that the speed is almost proportional to the radial distance. This means that the angular frequency, which is of the order of 0.1 rad/s (much larger than the fine-particle cyclotron frequency), is independent of the radial position. The frequency increases with an increase in the vertical magnetic field. The interparticle distance is observed to be almost constant during this rotation.

The rotation is observed for any shape of fine-particle clouds. The column-shaped fine-particle clouds rotate in the direction shown in Fig. 3. We cannot observe any rotation in the case of one row of string-shaped vertically aligned fine particles. When the number of the strings is more than 2, however, the vertical strings of fine particles show a clear rotation in the presence of the vertical magnetic field, as shown in Fig. 6, where we have three vertical strings of fine particles (top view). The rotation is found to be accompanied by radial oscillation. The ring-shaped fine-particle clouds, which are generated by using a radially segmented electrode for particle levitation and confinement, also rotate in the presence of the vertical magnetic field.

The rotation depends on the particle density. When the density is extremely low, there appears no rotation. The rotation starts when the density becomes high enough to provide the strong Coulomb coupling among the particles. The rotation frequency increases with an increase in the particle density. This means that this rotation is generated in the presence of the strong Coulomb coupling among the particles under the vertical magnetic field.

In this experiment, the magnetic field is so weak that there are no direct magnetic effects on fine-particle orbits, i.e., we can neglect the cyclotron motion of the particles. But, there are magnetic effects on electron and ion orbits, which could be necessary for the rotation of fine-particles clouds.

B. Rotation: Discharge plasmas

Here we demonstrate detailed measurements of the rotation of fine-particle clouds in the presence of the vertical

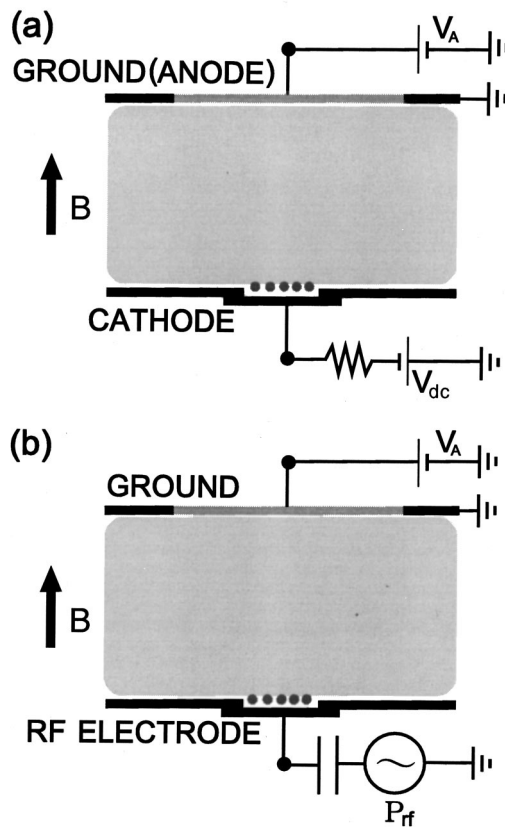


FIG. 7. Schematic of setups for experiments on fine-particle rotations in (a) dc and (b) rf discharge plasmas.

magnetic field. The measurements are performed on dc and rf discharge plasmas. Experimental configurations are quite simple, being different from our standard configuration in Fig. 1. The magnetic field is varied in a wide range from 0 to 40 kG. Experimental setups used are schematically described in Fig. 7, where (a) and (b) are setups for dc and rf discharge plasmas, respectively. In each setup, an upper electrode is segmented into two parts. The central part is a transparent disc electrode, to which an external voltage V_A is applied with respect to an outer ring electrode which is ground together with the vacuum chamber. Fine particles are levitated above the lower electrodes for the dc and rf discharges in the radially central region, as schematically shown in Fig. 7. We can control a radial potential profile by changing V_A , although this is accompanied by a change of plasma density profile. There is a vertical magnetic field B which induces the azimuthal rotation of fine-particle clouds. The same results have been obtained in both plasmas. Since it is more difficult to produce a stable symmetric dc discharge plasma under a very strong magnetic field, we present here the results only in the case of a rf discharge plasma.

The rotation is found to be very sensitive to V_A , as found in Fig. 8, where the angular frequency ω of the rotation is plotted as a function of V_A with the magnetic field B as a parameter. When V_A is negative (the potential of the central electrode is negative with respect to the ring electrode), the rotation is in the diamagnetic direction, being consistent with the results for the diffused plasmas described in Sec. II A1. When V_A is positive, on the other hand, the

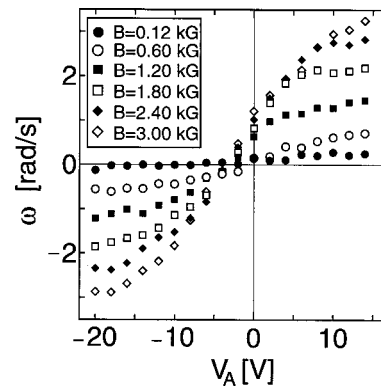


FIG. 8. Dependence of angular frequency ω of the rotation as a function of external potential difference V_A applied between central disc and outer ring electrodes with magnetic field B as a parameter. Gas pressure=76 mTorr, rf power=5 W.

rotation is in the paramagnetic direction. The angular frequency increases with an increase of the absolute value of V_A . The rotation is observed to stop around $V_A = -$ a few volts.

The angular frequency is found to increase with an increase in the vertical magnetic field. A dependence of the angular frequency ω on the vertical magnetic field B is presented at $V_A = 15$ and -15 V in Fig. 8, where B is varied up to 3 kG. We can observe the rotation even if B is so small as 0.05 kG. In such a small magnetic field, although electrons are magnetized, positive ions are only slightly magnetized. The angular frequency is found to be almost proportional to B up to 3 kG, where both electrons and positive ions are magnetized. In order to investigate this rotation for such a large value of B that there is a direct effect of B on fine particles, B is increased up to 40 kG. But, it is often quite difficult to produce stable symmetric (with respect to the vertical axis) plasmas when B is larger than 10 kG. The results in this measurement are presented at $V_A = 10$ and -10 V in Fig. 9. It is found in this figure that the angular frequency saturates when B is larger than 5 kG.

The rf power P_{rf} is also changed to learn the effect of the plasma density on the rotation. The results obtained are shown in Fig. 10. The angular frequency is found to increase with an increase in the rf power (see Fig. 11).

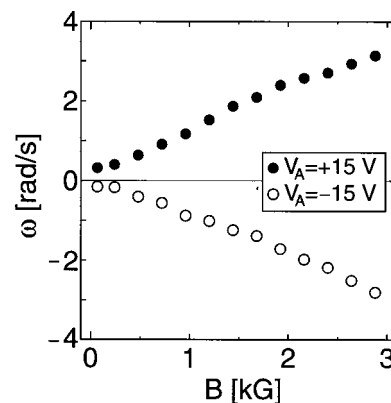


FIG. 9. Dependence of angular frequency ω of the rotation as a function of magnetic field up to 3 kG at $V_A = 15$ and -15 V. Gas pressure=76 mTorr, rf power=5 W.

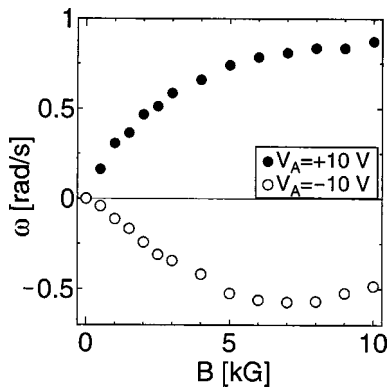


FIG. 10. Dependence of angular frequency ω of the rotation as a function of magnetic field up to 10 kG at $V_A = 10$ and -10 V. Gas pressure = 76 mTorr, rf power = 2 W.

III. DISCUSSIONS AND CONCLUSIONS

We have described our measurements of fine particles levitating in plasmas under the vertical magnetic field. For shape control of fine-particle clouds, the vertical magnetic field is very useful, generating vertically column-shaped fine-particle clouds and string-shaped vertically aligned fine particles. The application of the vertical magnetic field to strongly coupled fine-particle plasmas is always accompanied by a generation of the rotation of fine particles in the azimuthal direction on the horizontal plane.

According to our measurements, this rotation is due to an effect of plasmas on fine particles, which are modified by the magnetic field, even if the magnetic field is so strong that there is some direct effect of the magnetic field on fine particles. The results show that there is a drastic effect of V_A on the rotation. V_A modifies the radial potential profile, being also accompanied by a change of the radial plasma-density profile. But, the polarity change of V_A does not necessarily mean a change of the direction of the radial potential gradient. Our recent experiment also shows that the direction of the rotation changes when the radial density gradient is reversed for a fixed relatively flat potential profile in the radial direction. Here we have to remark that the potential profile in the radial region of particle levitation is always hill-shaped, being almost independent of the polarity and absolute value of V_A . The potential and density profiles are modified by V_A outside this region of particle levitation.

A mechanism of the rotation could be explained by taking account of ion trajectories modified by the magnetic field. In general, there might be two effects of the modification of ion trajectories. One of them is a change of the ion drag force on fine particles. There appears an azimuthal ion drag force in our plasmas because there are plasma potential and density gradients under the vertical magnetic field. The other is a change of the potential structure around the particles, which also has an effect on fine-particle motions in the azimuthal direction. Our results up to now could be understood by the azimuthal ion drag force due to the radial plasma potential and density gradients in the presence of the

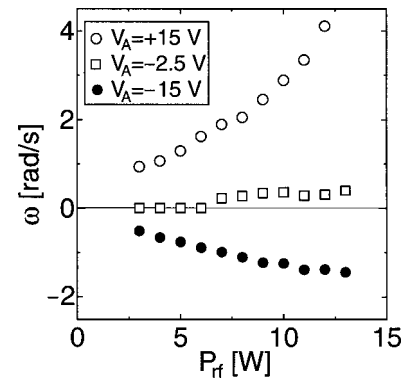


FIG. 11. Dependence of angular frequency ω of the rotation as a function of rf power P_{rf} for plasma production at $V_A = 15$, -2.5 , and -15 V. Vertical magnetic field = 1.2 kG. Gas pressure = 76 mTorr.

vertical magnetic field. It is reasonable to point out that the increase of the angular frequency with the rf power is due to an increase of the ion flux toward fine particles. Our recent measurements also show that the rotation speed decreases with an increase in the background gas pressure. This is due to effects of friction forces on ions and fine particles.

It is important to remark that the rotation is induced under the condition satisfying the strong Coulomb coupling among fine particles. This could be explained by the fact that a total force on fine-particle clouds is a sum up of forces on individual particles under such a condition.

In order to have a clear image about the mechanism, we must also take account of the finite ion Larmor radius because the rotation appears even when the ion Larmor radius is larger than the size of the fine-particle clouds. More measurements will be performed to understand the phenomena.

In conclusion, our experiments demonstrate drastic effects of a vertical magnetic field on fine particles levitating in plasmas. The shape control of fine-particle clouds provides interesting configurations for future investigations of fine-particle plasmas. Detailed features of the fine-particle rotation would be quite useful for understanding characteristic behaviors of fine particles in magnetized plasmas.

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